A Study on Nondestructive Evaluation Technique for Nuclear Facility by the Use of Interface wave

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Abstract. Guided wave was widely studied for plate and pipe due to the great potential to propagate over long distance with volume coverage. Guided wave even can propagate inaccessible area which cannot be inspected by conventional Ultrasonic Testing method. Shrink fit structure can be a problem to be inspected due to the geometric complication. In this paper, two pipes were designed with perfect shrink fit condition with Stainless Steel 316. The displacement distribution for in-plane and out-of-plane were calculated with boundary condition for shrink fitted structure. Multi transducer system is employed to investigate weld condition apart from transducer position. Complicate geometry for shrink fit structure is inspected by interface wave to identify defect location and size. The experimental result shows a possibility of weld delamination and defect detection. Artificial defects were properly detected with multi transducer interface wave inspection system with signal processing.

Introduction

Recently nuclear power plant safety issues become a great concern to the people. Nuclear power plant has been built several decays since the first time generates electricity by nuclear source. Nuclear power plant components are specially designed for their purpose. Therefore, those components need a unique inspection method to achieve high safety demands. Nuclear power plant components were inspected by Guided wave inspection method. \([1-3]\) On the nuclear reactor vessel, the control rod drive mechanism goes through nuclear reactor head. On that structure, those two structures are attached with shrink fit condition and weld at the end of shrink fit boundary. Reactor head is relatively thick to inspect by conventional UT technique from the outside of reactor. Therefore, reactor inside weld inspection is performed by the use of robot system due to the high radiation at the time scheduled in-service-inspection. However, for the new reactor design, proper inspection method should be presented for safety issue. In this paper, inaccessible reactor weld inspection method is applied by the use of interface wave and find reasonable reflection signal to evaluate the defects.

![Figure 1 Schematic of nuclear reactor vessel head weld and shrink fit structure](image-url)
Interface wave theory

The interface theory is very classical wave phenomena. The surface wave is a part of interface wave with half surface media. In the case of two interfaces with bounded media, we can use two boundary condition as upper and bottom media material properties. Stoneley wave is particularly propagating interface between solid and liquid media. However, in this paper, two solid media have shrink fit condition. Therefore boundary condition is assumed as solid state with shrink fit boundary. The displacement of interface wave on the plate is below. [4]

\[
 u = u(z)e^{i(kx - \omega t)}, \quad w = w(z)e^{i(kx - \omega t)}
\]  

(1)

where \(u\) and \(w\) is displacement on \(x\) and \(z\) direction. Coordination system is followed as figure 2. Unknown amplitude \(u(z)\) and \(w(z)\) can be define as eq.(2)

\[
 u(z) = \{[Ae^{-kaz} + Be^{kaz}] - \beta(Ce^{-k\beta z} - De^{k\beta z})\}e^{i(\omega t - kz)}
\]

\[
 w(z) = i[\alpha(Ae^{-kaz} - Be^{kaz}) - (Ce^{-k\beta z} + De^{k\beta z})]e^{i(\omega t - kz)}
\]

(2)

where \(\alpha^2 = 1 - c^2/\varepsilon_L^2\), \(\beta^2 = 1 - c^2/c_T^2\), \(c/\omega/k\)

![Figure 2 Coordinate of interface media 1 and media 2](image)

The stress component is derived as eq (3)

\[
 \sigma_z = i\mu(-k(1 + \beta^2)(Ae^{-kaz} + Be^{kaz}) + 2k\beta(Ce^{-k\beta z} - De^{k\beta z}))e^{i(\omega t - kz)}
\]

\[
 \sigma_{xz} = \mu(-2k\alpha(Ae^{-kaz} - Be^{kaz}) + k(1 + \beta^2)(Ce^{-k\beta z} + De^{k\beta z}))e^{i(\omega t - kz)}
\]

(3)

The boundary condition on the interface between media 1 and 2 can be set as below

\[
 u^{(1)} = u^{(2)} \quad \sigma_z^{(1)} = \sigma_z^{(2)}
\]

\[
 w^{(1)} = w^{(2)} \quad \sigma_{xz}^{(1)} = \sigma_{xz}^{(2)}
\]

where superscript (1) and (2) indicate media 1 and 2, respectively.

To satisfy boundary condition, when \(z=0\), the system equation (4) will have a nontrivial solution when determinant is zero.
\[
\begin{bmatrix}
\sigma_z^{(1)} - \sigma_z^{(2)} \\
\sigma_{x}^{(1)} - \sigma_{x}^{(2)} \\
u^{(1)} - u^{(2)} \\
w^{(1)} - w^{(2)}
\end{bmatrix}
= \begin{bmatrix}
-(1 + \beta_1^2) & -2\beta_1 & (1 + \beta_2^2)g & -2\beta_2g \\
2\alpha_1 & (1 + \beta_1^2) & 2\alpha_2g & -(1 + \beta_2^2)g \\
1 & \beta_1 & -1 & \beta_2 \\
-\alpha_1 & -1 & -\alpha_2 & 1
\end{bmatrix}
\begin{bmatrix}
B_1 \\
D_1 \\
A_2 \\
C_2
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
0 \\
0
\end{bmatrix}
\quad \text{for} \quad (4)
\]

For the structure which is used for this paper is stainless steel 316. Figure 3 shows wave structure of stainless steel 316 from the interface of two layered structure. The out of plane displacement on the interface was the maximum while getting far from the interface out of plane displacement becomes zero. In the case of this research, two layered structure has same material, so that upper and lower layer wave structure is symmetric.

Figure 3 Wave structure of Stainless steel 316 interface, u is in-plane displacement and w is out-of-plane displacement.

**Experimental Setup**

Figure 4 shows experimental setup for interface wave inspection for shrink fit condition structure. Tone burst signal was used to generate interface wave on this structure and it propagate along the interface between two structure layers and reflect back from the weld on the other side of structure. Also artificial defects were employed to verify resolution of interface wave inspection technique. Figure 5 shows defect location and size information. To generate defects on the interface, drill hole defect was manufactured on the specimen. [5, 6]
Figure 5 Defect location and size information for experiment specimen. Defect size is following,
① axial depth: 9 mm, Φ 7.

Experimental result

Interface wave has directional propagation path on the specimen. Figure 6 shows the interface profile with respect to circumferential angle. The interface wave was generated at 0 degree from one side of specimen which before shrink fit condition starts and received at after shrink fit condition. The interface wave propagates at most 60 degree directional beam size and at this propagation distance, 500 mm, it does not diverse at the bottom surface.

Figure 6 Beam size inspection result at the end of specimen

To verify interface wave inspection resolution, defect axial depth 9 mm, Φ 4 was investigated. Figure 7 shows interface wave signal on defect area and no-defect area. Interface wave velocity on this material is 2.75 mm/μs and time of flight difference is 3.2 μs. Defect size is 0.2 mm and error is only 2 percentage. Therefore the experimental result shows possibility on shrink fitted structure by the use of interface wave.
Conclusion

Shrink fit condition structure is difficult inspect by traditional ultrasonic testing technique. In the case of this research, specimen is relatively long to inspect by UT technique. Therefore, interface wave inspection technique can be alternative solution to inspect inaccessible shrink fit structure. By the use of interface wave, it has directional wave propagation path, so that it can be used to inspect defect on the other side of specimen. Further research need to be performed to verify interface wave inspection resolution and sensitivity analysis on different type of defects.

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References